

# Nuclear PDFs in the beginning of the LHC era

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## Abstract

The status of the global fits of nuclear parton distributions (nPDFs) is reviewed. In addition to comparing the contemporary analyses of nPDFs, difficulties and controversies posed by the neutrino-nucleus deeply inelastic scattering data is overviewed. At the end, the first dijet data from the LHC proton+lead collisions is briefly discussed.

## 1. Introduction

The experimental evidence for the appearance of non-trivial nuclear modifications in hard-process cross sections is nowadays well known. The “canonical” example is the deeply inelastic scattering (DIS), in which the ratio  $\sigma(\ell^\pm + \text{nucleus})/\sigma(\ell^\pm + \text{deuteron})$  displays the typical pattern of nuclear effects [1]: small- $x$  shadowing, antishadowing, EMC-effect, and Fermi motion. A cartoonic picture is shown in Fig. 1. The central theme in the global analyses of nuclear parton distributions

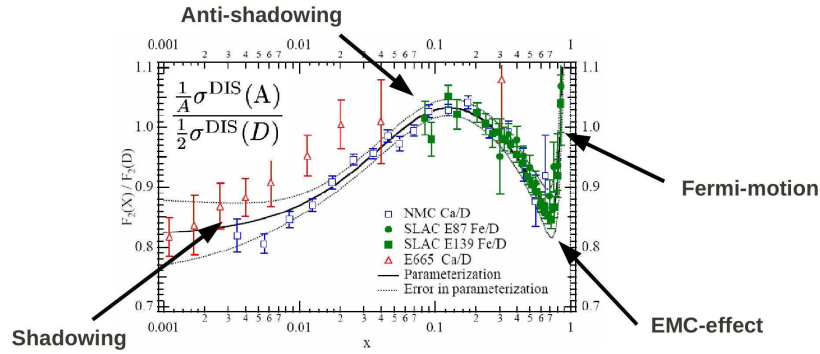


Figure 1: Typical nuclear effects seen in the DIS measurements.

$f_i^A$  (nPDFs), is to find out whether, and to what extent (in which processes, in which kinematic conditions) such effects can be interpreted in terms of standard collinear factorization [2, 3], for example, in the case of DIS,

$$\sigma_{\text{DIS}}^{\ell+A} = \sum_i \underbrace{f_i^A(\mu_{\text{fact}}^2)}_{\text{nuclear PDFs, obey the usual DGLAP}} \otimes \underbrace{\hat{\sigma}_{\text{DIS}}^{\ell+i}(\mu_{\text{fact}}^2, \mu_{\text{ren}}^2)}_{\text{usual pQCD coefficient functions}} + \mathcal{O}(1/Q^n), \quad (1)$$

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where the partonic coefficient functions  $\hat{\sigma}$  and the DGLAP evolution [4, 5, 6, 7] of  $f_i^A$  are the same as in the case of free proton scattering. In short, the goal is to carry out very similar program as in the case of free proton analyses [8, 9, 10, 11]. The main obstacle in drawing definite conclusions regarding the adequacy of factorization in nuclear environment has been the shortage of suitable hard-process data as, in comparison to the free proton case, the amount, kinematic reach, and variety of experimental data is rather restricted. In fact, it is only very recently — especially along the discussion surrounding the neutrino-nucleus DIS (see later) — that the nPDF process independence has been put to a serious test. In the near future, the LHC proton-lead hard-process data [12], once available in their full glory, are expected to provide definitive answers. The theoretical expectations are that the  $Q^{-n}$ -type power corrections in Eq. (1) become enhanced in nuclear environment and could eventually be seen even at perturbative scales [13]. The search for such a transition from the linear DGLAP dynamics to a non-linear regime is also one of the main goals of the LHC proton+lead program [14, 15].

## 2. A brief overview of the existing analyses of nuclear PDFs

The latest available next-to-leading order (NLO) nPDFs are HKN07 [16], EPS09 [17], and DSSZ [18]. Also the work of nCTEQ collaboration [19, 20, 21] will be commented, although their final pre-LHC parametrization is not yet available. Some characteristics of these NLO fits are summarized in Table 1.

Table 1: Key characteristics of the contemporary nPDF fits (the nCTEQ column corresponds to the presentation given in DIS2013, Marseille [21]).

	HKN07	EPS09	DSSZ	NCTEQ
Order in $\alpha_s$	LO & NLO	LO & NLO	NLO	NLO
Neutral current DIS $\ell+A/\ell+d$	✓	✓	✓	✓
Drell-Yan dilepton $p+A/p+d$	✓	✓	✓	✓
RHIC pions $d+Au/p+p$		✓	✓	
Neutrino-nucleus DIS			✓	
$Q^2$ cut in DIS	1 GeV	1.3 GeV	1 GeV	2 GeV
datapoints	1241	929	1579	708
free parameters	12	15	25	17
error analysis	✓	✓	✓	✓
error tolerance $\Delta\chi^2$	13.7	50	30	35
Free proton baseline PDFs	MRST98	CTEQ6.1	MSTW2008	CTEQ6M-like
Heavy quark treatment	ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS

The nPDFs  $f_i^A$  are linear combinations of bound proton ( $f_i^{p,A}$ ) and bound neutron ( $f_i^{n,A}$ ) PDFs

$$f_i^A(x, Q^2) = \left(\frac{Z}{A}\right) f_i^{p,A}(x, Q^2) + \left(\frac{N}{A}\right) f_i^{n,A}(x, Q^2), \quad (2)$$

where  $Z$  is the number of protons and  $N$  the number of neutrons in the nucleus  $A$ . The relation between the bound proton PDFs and the free nucleon baseline  $f_i^p$  is usually expressed as

$$f_i^{p,A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2), \quad (3)$$

where  $R_i^A(x, Q^2)$  quantifies the nuclear modification (also impact-parameter dependent versions has been suggested, see Ref. [22]). For the moment, all groups rely on the isospin symmetry to obtain the bound neutron PDFs (e.g.  $f_u^{n,A} = f_d^{p,A}$ ) — an assumption that would need to be revised once the QED effects are included in the parton evolution [23, 24, 25, 26]. All but HKN07 assume no nuclear modification for the deuteron,  $R_i^{\text{deuteron}}(x, Q^2) = 1$ . Although small, the nuclear effects in deuteron are still non-zero, and have some importance when the deuteron data are included in the free proton fits [27].

Different groups use different functions to parametrize  $R_i^A(x, Q_0^2)$ . For example, while EPS09 employs a piecewise fit function (as a function of  $x$ ), DSSZ uses a single fit function constructed such that the analytic Mellin transform exists. In the works of nCTEQ,  $f_i^{p,A}(x, Q_0^2)$  is parametrized directly with the same fit function as used for their free proton baseline. However, as the free proton baseline is taken as “frozen”, this is simply another way of parametrizing  $R_i^A(x, Q_0^2)$ .

Most of the data that are used as constraints in the nPDF fits come as nuclear ratios similar to that shown in Fig. 1. What makes such ratios especially appealing is that they prove remarkably inert to the higher order pQCD corrections. Also, the dependence of the free proton baseline PDFs gets reduced. The exception here are the neutrino-nucleus DIS data, included in the DSSZ fit, that are only available as absolute cross-sections (or as corresponding structure functions derived from those). The inclusion of these data also requires using a general-mass variable-flavor-number scheme (GM-VFNS) for treating the heavy quarks overtaking the zero-mass scheme (ZM-VFNS) employed in the older fits (EPS09, HKN07).

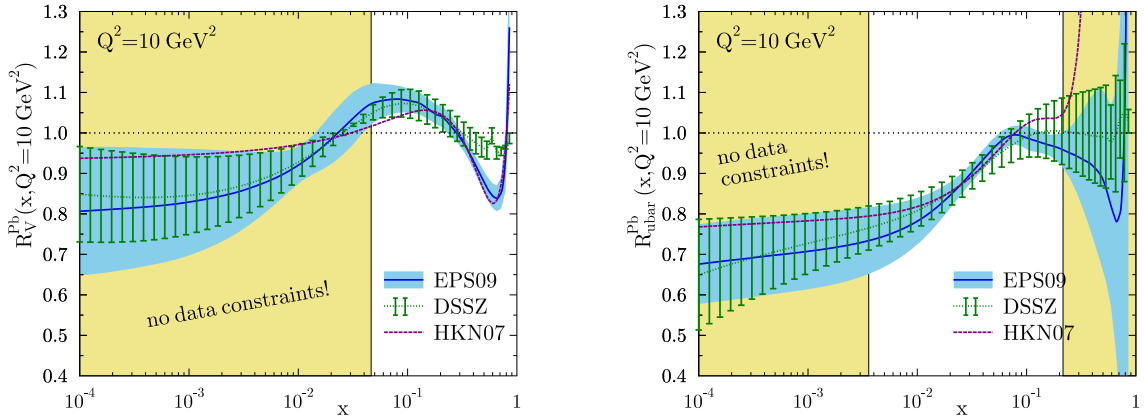


Figure 2: Comparison of up valence and sea quark nuclear modification factors for the lead nucleus at  $Q^2 = 10 \text{ GeV}^2$ . Blue line with error band is EPS09, green dotted line with error bars DSSZ, and purple dashed HKN07.

A comparison of the  $R_{uV}^{Pb}(x, Q^2 = 10 \text{ GeV}^2)$  (up valence) and  $R_{u\bar{u}}^{Pb}(x, Q^2 = 10 \text{ GeV}^2)$  (up sea) from the available parametrizations is presented in Fig. 2. The areas with yellow background are those regions of  $x$  where the direct data constraints do not exist or they are very weak. In these regions the bias due to the assumed form of the fit function and parameter fixing may be significant. Whereas the  $R_{uV}^A$  from EPS09 and HKN07 agree at large  $x$ , DSSZ, strangely enough, is clearly above at  $x \simeq 0.5$ . This is rather unexpected as in this EMC region there are plenty of data constraints from DIS experiments. The same behaviour is there already in the DSSZ precursor, NDS [28], and the probable source of this has been identified as a misinterpretation of the isospin

correction that the experiments have applied to the data<sup>1</sup>. In EPS09 and HKN07 the assumption  $R_{u_V}^A(x, Q_0^2) = R_{d_V}^A(x, Q_0^2)$  was made as only one type of data sensitive to the large- $x$  valence quarks was included in these fits. Indeed, at large  $x$ , one can approximate

$$d\sigma_{\text{DIS}}^{\ell+A} \propto \left(\frac{4}{9}\right) u_V^A + \left(\frac{1}{9}\right) d_V^A \propto u_V^p \left[ R_{u_V}^A + R_{d_V}^A \frac{d_V^p}{u_V^p} \frac{Z+4N}{N+4Z} \right] \approx u_V^p \left[ R_{u_V}^A + \frac{1}{2} R_{d_V}^A \right], \quad (4)$$

which underscores the fact that these data can constrain only a certain linear combination of  $R_{u_V}^A$  and  $R_{d_V}^A$ . Despite the lack of other type of data sensitive to the valence quarks, the assumption  $R_{u_V}^A(x, Q_0^2) = R_{d_V}^A(x, Q_0^2)$  was released in a recent nCTEQ work leading to mutually wildly different  $R_{u_V}^A$  and  $R_{d_V}^A$  (see Fig.1 in Ref.[21]). Other type of data sensitive to the valence quarks would obviously be required to pin down them separately in a more realistic manner. Despite the fact that some neutrino data (also sensitive to the valence quarks) was included in the DSSZ fit, the authors did not investigate the possible difference between  $R_{u_V}^A$  and  $R_{d_V}^A$ .

In the case of  $R_u^A$ , which here generally represents the sea quark modification, all parametrizations are in a fair agreement in the data-constrained region. This is also true if the nCTEQ results are considered (Fig.1 in Ref.[21]). Above the parametrization scale  $Q^2 > Q_0^2$ , the sea quark modifications are also significantly affected, especially at large  $x$  ( $x \gtrsim 0.2$ ), by the corresponding gluon modification  $R_g^A$  via the DGLAP evolution.

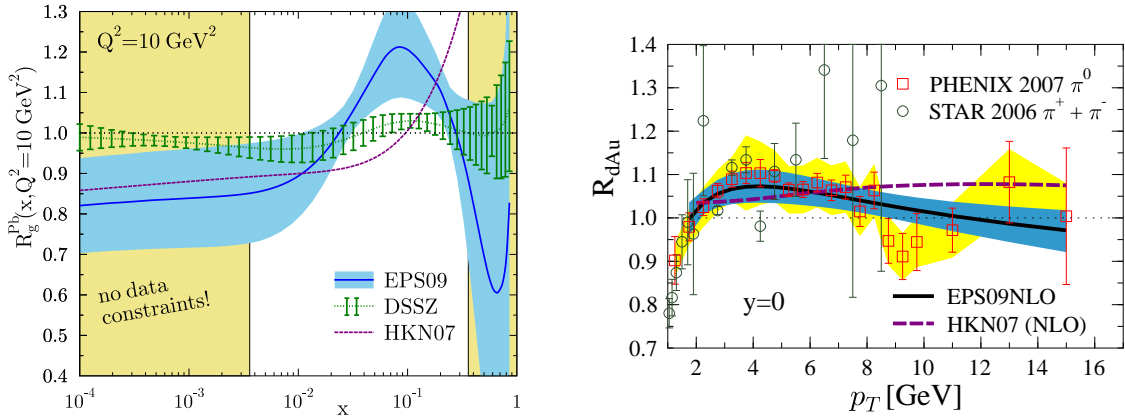


Figure 3: Comparison of the gluon nuclear modification factors for the lead nucleus at  $Q^2 = 10 \text{ GeV}^2$  (left), and the nuclear modification for inclusive pion production in d+Au collisions at midrapidity (right).

The largest differences among EPS09, HKN07, and DSSZ are in the nuclear effects for the gluon PDFs, shown in Fig. 3. The origins of the large differences are more or less known: The DIS and Drell-Yan data are mainly sensitive to the quarks, and thus leave  $R_g^A$  quite unconstrained. To improve on this, EPS09 and DSSZ make use of the nuclear modification observed in the inclusive pion production at RHIC [29, 30]. An example of these data are shown in Fig. 3. Although the pion data included in EPS09 and DSSZ are not exactly the same, it may still look surprising how different the resulting  $R_g^A$  are. The reason lies (as noted also e.g. in [31]) in the use of different

<sup>1</sup>M. Stratmann and P. Zurita, priv.comm.

parton-to-pion fragmentation functions (FFs)  $D^{k \rightarrow \pi+X}(z, Q^2)$  in the calculation of the inclusive pion production cross sections

$$d\sigma^{\text{d+Au} \rightarrow \pi+X} = \sum_{i,j,k} f_i^{\text{d}} \otimes d\hat{\sigma}^{ij \rightarrow k} \otimes f_j^{\text{Au}} \otimes D^{k \rightarrow \pi+X}. \quad (5)$$

While in EPS09 the KKP [32] vacuum FFs (determined solely from the  $e^+e^-$  data) were used, DSSZ advocated the use of nuclear modified FFs [33] determined from the very *same* pion data that was later on included in the DSSZ nPDF fit. Therefore, they were condemned to find a very similar  $R_g^A$  that was used in the fit for the nuclear modified FFs, namely that of NDS. While both EPS09 and DSSZ can describe the pion data, the physics content is rather different (initial state effect in EPS09, final state effect in DSSZ). The nCTEQ result for the gluons (Fig.1 in Ref.[21]) comes with clearly larger uncertainty than the ones in EPS09 or DSSZ. This is mainly due to the larger  $Q^2$  cut for the DIS data and that they do not currently include the pion data.

### 3. The case of neutrino-nucleus DIS data

A nPDF-related issue that has caused some stir during the recent years concerns the compatibility of the neutrino-nucleus DIS data with the other nuclear data (used e.g. in EPS09). The whole discussion was initiated in [34] where a PDF fit to the NuTeV neutrino+iron DIS data [35] was reported. The results seemed to point towards nuclear modifications in PDFs different from those obtained in charged-lepton-induced reactions. Later on, it was argued [20] that these two types of data display clear mutual tension, and, even a breakdown of the collinear factorization was flashed as a possible explanation. Such would have far reaching consequences as the all major free proton groups [9, 10, 11] do include neutrino data in their fits, thereby silently assuming the validity of the factorization there. The authors underscored accounting for the NuTeV data correlations via the provided covariance matrix although the same conclusion was reached when all the errors were added in quadrature.

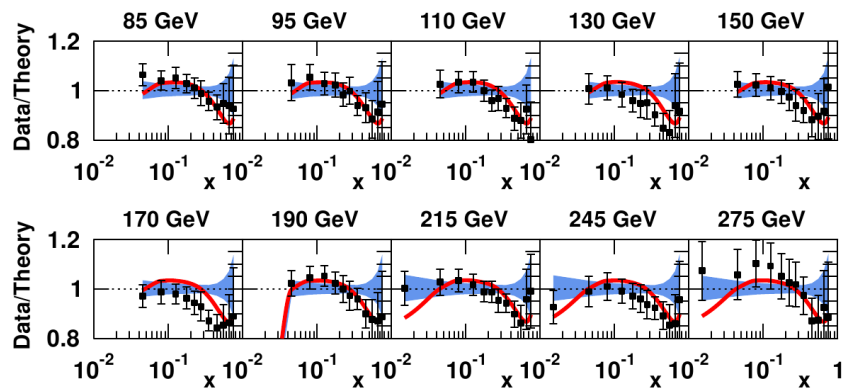


Figure 4: An example of the  $Q^2$ -averaged nuclear modifications derived from the NuTeV data. The data points correspond to the data divided by NLO calculations with CTEQ6.6 PDFs without nuclear effects, and the blue band is the CTEQ6.6 uncertainty band. The red lines are predictions based on EPS09. Each panel corresponds to a different neutrino beam energy.

In [36] a somewhat different strategy was adopted. Instead of concentrating on one data set only, this study aimed for a more global picture by using also neutrino data from the CHORUS

[37] and CDHSW [38] experiments. By confronting the existing sets of nuclear PDFs with these data, no obvious difficulty to reproduce them was detected — the overall agreement seemed to be good. However, the NuTeV cross sections were found to contain rather large, neutrino-energy dependent fluctuations. Such fluctuations were found upon inspecting the nuclear modifications  $\sigma(\text{experimental})/\sigma(\text{theory})$  as a function of  $x$ , averaged over  $Q^2$ . Examples of such ratios in the case of NuTeV data are shown in Fig. 4. Unexpected fluctuations between different neutrino beam energies are clearly visible.

A solution to all this was proposed in [39]. The central idea was to look (for each neutrino beam energy  $E_\nu$  separately) the cross sections normalized by the total cross section (integrated over  $x$  and  $Q^2$ ) — nothing more extraordinary than e.g. measuring the shape of the dilepton distributions at the LHC [40] or Tevatron [41]. Fig. 5 illustrates the effect, presenting the nuclear

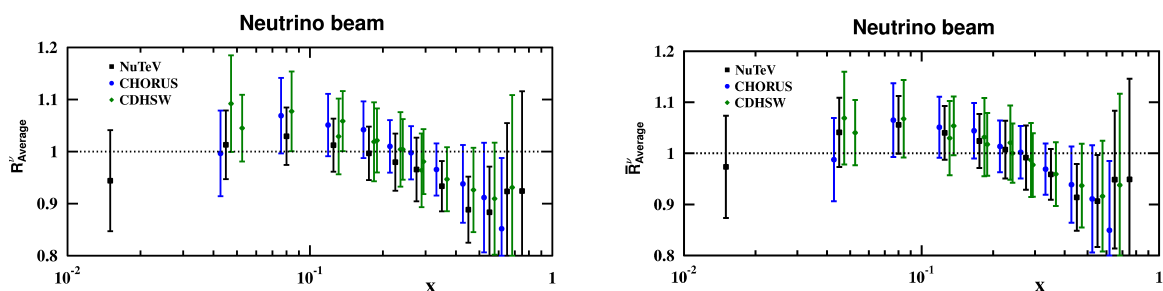


Figure 5: Neutrino data (averaged over  $Q^2$  and  $E_\nu$ ) without the normalization (left-hand panel), and with the normalization (right-hand panel). The CHORUS (blue circles) and CDHSW (green diamonds) data has been horizontally slightly shifted from the NuTeV (black squares) data points.

modifications (averaged over  $Q^2$  and  $E_\nu$ ), first, obtained without the normalization (left), and then, after applying the normalization procedure (right). The normalization process definitely improves the mutual agreement among the independent data sets, and implies that, apart from the normalization, the  $x$  and  $Q^2$  dependence of all the data appear to agree. The compatibility of these data with the nuclear PDFs (CTEQ6.6+EPS09) was studied employing a novel re-weighting technique (reminiscent of similar methods developed in Refs. [42, 43, 44]). While supporting the compatibility, the method also confirmed the same incompatibility as found in the nCTEQ work when the normalization was not applied.

A third point-of-view is provided by the authors of DSSZ who actually went and included neutrino data (also NuTeV data) in their nPDF fit without an obvious difficulty. This may seem surprising now that the difficulties posed by the NuTeV data appear confirmed. Three issues contributing can be readily identified: the use of structure functions instead of the absolute cross sections (much less data), the use of MSTW2008 PDFs [9] as a baseline (already constrained by the NuTeV data), and adding the MSTW2008 PDF uncertainties on top of the experimental errors. All this makes the neutrino data less important in comparison to the other data and may thereby obscure the difficulties that the NuTeV data poses.

#### 4. The first glimpse of nuclear PDFs at the LHC?

The first experimental results from the LHC proton+lead run are now starting to become public [12], and are expected to conclusively test the universality of the nPDFs and hopefully serve as further constraints as well. For instance, different rapidity and transverse momentum distributions

of charged leptons from electroweak gauge boson decays have been theoretically explored [45, 46, 47, 48, 49] and promise to probe various aspects of nPDFs. Direct photons, inclusive hadrons and jet observables [50, 51, 52, 53, 54, 55] have been predicted to retain sensitivity to the nuclear modifications in PDFs as well. However, the first hard QCD-process data set from the 2013 proton+lead run that can be directly compared to the nPDF predictions at the NLO level is the shape of the pseudorapidity distribution of dijets measured by the CMS collaboration [56]. The dijet pseudorapidity  $\eta_{\text{dijet}}$  is defined as the average of the leading and subleading jet pseudorapidities,

$$\eta_{\text{dijet}} \equiv (\eta_{\text{leading}} + \eta_{\text{subleading}})/2, \quad (6)$$

within the acceptance  $|\eta_{\text{leading,subleading}}| < 3$ . The transverse momenta of the jets are large,  $p_{T,\text{leading}} > 120 \text{ GeV}$ ,  $p_{T,\text{subleading}} > 30 \text{ GeV}$ , and the rather narrow cone size  $R = 0.3$  used in defining the jet within the anti- $k_T$  algorithm, suppresses the uncertainties from the underlying event. The corresponding pQCD predictions appeared in Ref. [57] where it was observed that this particular observable — not being an absolute cross section but a normalized one — is surprisingly inert to the higher order pQCD corrections but still retains sensitivity to the nuclear modifications in PDFs. These predictions are, in Fig. 6, compared to the preliminary data taken from Ref. [56]. In comparison to the calculation with just CT10 PDFs with no nuclear effects (orange dashed line)

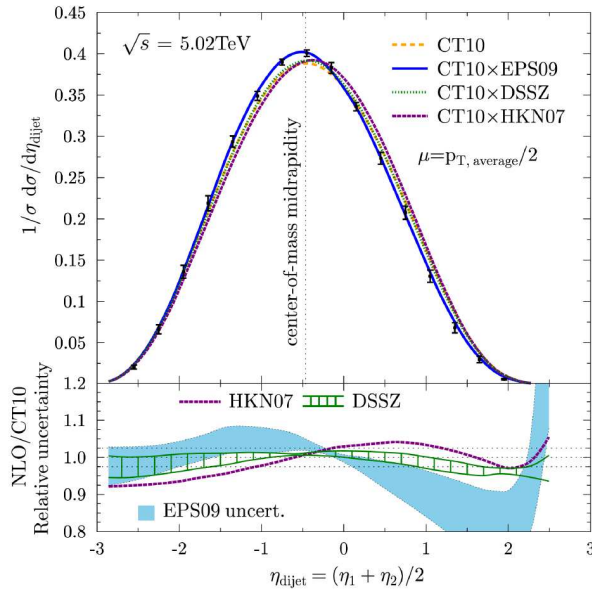


Figure 6: The preliminary dijet rapidity distribution from CMS (read “by eye“ from [56]) compared to the calculations [57] with no nuclear effects (orange dotted), with EPS09 (solid blue), HKN07 (purple long dashed), and DSSZ (green dotted).

the preliminary data shows a clear enhancement in the backward direction and suppression in the forward direction. These are readily explained by an antishadowing and EMC effect in the gluon PDFs, similar to those in EPS09, as the good agreement with the preliminary data and the calculation with EPS09 (blue solid curve) demonstrates. The nuclear effects in DSSZ are too weak to reproduce the data (green dotted line), and HKN07 makes a correction to a wrong direction (purple dashed line). The bottom line here is that the same nuclear modifications required to reproduce



the inclusive pion data (Fig. 3) at  $\sqrt{s} = 200$  GeV at rather low transverse momenta,  $p_T < 20$  GeV, are supported by these preliminary dijet data with  $\sqrt{s} = 5.02$  TeV and  $p_T \gtrsim 100$  GeV. This is evidence of the nPDF universality and also seems to indicate that there cannot be significant nuclear modifications in the parton-to-hadron FFs like those proposed in [33].

The role of nPDFs in the LHC lead+lead program is not as evident as it is in proton+lead collisions. However, it is encouraging that even in this case the existing measurements for high- $p_T$  electroweak observables are consistent with the pQCD predictions [58, 59, 60, 61], the data uncertainties being admittedly still rather large. Such observations give further confidence to the use of collinear factorization e.g. in computing the initial condition needed for subsequent hydro-dynamical evolution [62], or in estimating the backgrounds when charting different sources of low- $p_T$  photons [63, 64] in heavy-ion collisions.

## 5. Summary

The present status of the nPDFs was reviewed. Sizable differences among the independent parametrizations exist reflecting the significant prevailing uncertainty. To definitely reduce these uncertainties, more data are needed. In this respect, data from the LHC proton-lead run are foreseen to bring significant additional insight. Indeed, already the very first dijet data from the CMS collaboration, briefly mentioned here, could help to discriminate between the existing sets of nPDFs. The long-standing issue concerning the neutrino-nucleus DIS was also shortly recalled for which a possible solution has been recently proposed and could eventually lead to a more comprehensive use of these data in global fits of nPDFs.

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